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Electronics Technology Division
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FOREWORD

This report was prepared at Spacelabs, Inc., Van Nuys, California. The principal investigator was George H. Sullivan, M.D. The study, research and development of the prototype system were carried out under Contract AF33(657)-7771, Project Number 4160, Task Number 416002.

The contract was monitored by Dr. Mildred B. Mitchell, Research Psychologist, Bionics Section, Bionics and Computer Branch, Electronics Technology Laboratory. Work on this program was conducted between 1 November 1961 and December 29, 1962.

The authors acknowledge the significant contribution made by Dr. John Lyman and Mr. Franklyn C. DeBiasio of the Biotechnology Laboratory, Department of Engineering, University of California, Los Angeles.

This is the final report on the contract.

ABSTRACT

The object of the program was the demonstration of feasibility of the myoelectric control of a servo boost system to position the operator's hand. The basic arm movements desired and the muscles involved were determined and the myoelectric activity patterns characteristic of the movements measured. Transforms were performed on the "raw" signals and control logics which relate myoelectric signals to desired servo action were written. A task simulator was constructed which accepted the myoelectric inputs from sets of three or four muscles, performed the present logic on the elicited myoelectric signals, provided success-failure feedback, and drove an arm support splint in uniplanar up-down movement.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

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SECTION I

INTRODUCTION

GENERAL

In general terms, the interaction between a human operator and a machine can be thought of as occurring at a "man-machine interface." From the machine side, this interface is bridged by displays which act upon the operator's sensory organs; from the operator's side, by effectors applied to the machine's controls. The man affects the machine through control inputs, usually by the use of manually applied forces or displacements to the machine control through aircraft sticks, steering wheels, or even pushbuttons.

The opportunity and requirement for manual control of a spacecraft were identified in the recent orbital flights where manual or "fly by wire" control was necessary for completion of the flight. In these orbital flights, manual control took place in situations of weightlessness where free movement of the extremities was unimpeded. However, there are environmental conditions where man, unassisted by a servo boost system, may be ineffectual in machine control.

In high accelerative-decelerative force fields, it would be difficult for the human operator to make rapid and accurate corrections to the craft's flight path during long periods of deceleration, as may be experienced on re-entry into the earth's atmosphere following an earth orbital flight. The operator subjected to perhaps 5-8 transverse G's finds that he no longer can respond rapidly or accurately in positioning his arms in space to undertake control measures. The affector link, the operator's vision, as one example, may function normally under those conditions, but his ability to respond to a presented problem with purposeful arm movements may require mechanical support and assistance in order to close the effector link.

The additional physical effort required for arm movement and the concomitant pilot fatigue that is experienced in a fully pressurized protective garment reduce the operator's efficiency. An automatically controlled servo boost system will facilitate the natural movements of the suit wearer. These conditions are ideal for the judicious application of a myoelectric control system to provide the basic input for closing the effector link. The pilot attempting a purposeful muscular action of his extremities provides a signal in the form of myoelectric potentials which may be used as the input to a logic control system. The system output, in turn, may be used to control the mechanically supported and aided movement of the extremities. The visual feedback to the operator of the position of the extremities enables him to limit voluntarily the genesis of the myoelectric potentials when the intended action is achieved.

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OBJECTIVE

The objective of the technical effort involved two major areas of investigation. The first was the selecting of basic arm movements and the muscles to be instrumented, determining both the activity patterns characteristic of the movements and the optimum means of transforming the "raw" myoelectric signals for servo-system use. In addition, control logics were to be formulated which relate the myoelectric potentials to the desired servo action.

The second major effort was directed towards defining for a simulated task the degree of precision in control actions which could be obtained through the myoelectric transforms.

SECTION II

TECHNICAL APPROACH

BACKGROUND

The basic electrical properties of the myoelectric potential for a maximal contraction of an average size muscle when detected at the skin surface have been found to be as follows:

Total Bandpass	3-1000 cps
Bandpass of Maximum Signal Power	10-200 cps
Amplitude (peak to peak)	1-3 mv

Myoelectric activity can be easily detected by the application of conductive plates to the skin area over a contracting muscle. Traditionally, the electrodes used have been relatively heavy plates, and have contributed greatly to recording artifact while making long-term recording difficult. However, an extremely low mass, flexible foil electrode developed by Sullivan and Weltman (4) permits the instrumentation of an unprecedented number of arm sites and results in an improved signal to noise ratio in the signal.

The myoelectric signal impressed across a set of electrodes when amplified and displayed appears as a spiked, randomly varying voltage level. The peak to peak amplitude of the displayed signal is associated with various ranges of muscle activity from complete relaxation to voluntary contraction.

The useful myoelectric control signal exists only in the voluntary contraction range with an amplitude of 60 to 3000 microvolts. The relaxation and psychological stimuli signals are buried in the "noise" (observed at 20 to 30 microvolts) normally found at the body surfaces. Voluntary effort can entail either an attempt at arm movement (resulting in a "natural" pattern of myoelectric activity over a selected set of muscles), or a practiced isometric contraction of specific muscles (again yielding a pattern of activity). In both situations, one natural and one trained, it is necessary for a following servo system to make use of the total pattern of activity. The alternative to the use of several muscles as "signal sites, " if more than one servo action is desired, is to use one muscle and a temporal code (e.g., Morse) whereby bursts of activity in a specified sequence initiate servo action. Temporal coding, however, is an inefficient and slow technique.

Traditional measures, such as the peak-to-peak amplitude of the raw signal, are suited neither to differentiation of activity and inactivity nor to servo use. However, a number of electronic transformations exist which materially increase the reliability of pattern recognition. The smoothing transformations in particular seem to yield a signal suitable for control use (5).

EXPERIMENTAL PROGRAM

The myoelectric control of a servo boost system to position the operator's hand was selected as the most direct approach to the generalized problem of myoelectric control. Accordingly, the planned experimental program was directed towards the acquisition of data necessary for demonstrating the feasibility of this approach.

It is probable that manual controls will not be positioned within the whole volume of a manned capsule but rather the region of interest is roughly the spherical surface swept out by the operator's hand with the arm comfortably extended and limited by his functional visual range. The experimental program was restricted to this area on the assumption that instruments would be confined to this curved surface. An additional requirement of the program was that the hand, on reaching a selected position on the curve, would remain stable without continuous effort. Initiation of new myoelectric activity would be necessary to move from a stable point.

Derivation of ON-OFF Control Logics

The experimental study of this program was divided into two phases. The first phase was conducted in conjunction with the Biotechnology Laboratory of the University of California Los Angeles. The experimental objective was the derivation of ON-OFF Control logics for a sub-group of most useful arm movements. Phase Two was conducted by Spacelabs at its facilities and consisted of static task simulation, dynamic uniplanar task control simulation, and manipulative task simulation.

The control logics for Phase One were formulated in the following manner: myoelectric signals detected at six muscle sites were tape recorded during arm maneuvers for simulated 1-G, 3-G, and 6-G conditions. Continuous movements within the available arm range were simulated by movements initiated from predetermined static arm positions. The tape recorded signals were smoothed by low-pass filters, displayed on oscillograph paper, and their peak values transcribed into detailed tables. Threshold values were chosen for each muscle and the observed signal amplitudes converted to the binary notation "O" (sub-threshold) and "1" (supra-threshold). Binary tables were determined for each subject. From the detailed binary tables, other tables were derived which permitted stepwise elimination of the Position and Subject variables. Thus, the final logics represent a guide for subsequent system design and operator training, rather than a literal transcription of observed patterns.

Task Simulation

The experimentation in Phase Two, Task Simulation, followed from the results of the initial phase.

Static Task Simulation - Simulations of a four-movement myoelectric control task were accomplished by combining a programmable central logic unit with a visual feedback display. The simulator was used both to evaluate the logics suggested in Phase I by use of a success-probability criterion and as a means of estimating reliability of myoelectric control over the available arm position range. Reliability was studied as a function of training and an additional control logic derived.

Dynamic Uniplanar Task Control Simulation - Since the crucial question in myoelectric control is whether or not the operator can adequately position a moving servoed brace, a uniplanar dynamic task was constructed and used to evaluate performance. The simulator was designed for up-down motion, and provided a direct contrast with the equivalent control actions under static conditions.

Manipulative Task Situation - While myoelectrically controlled arm movement itself is of interest, the practical objective of this movement is to place the hand in a position to operate a switch, a knob, a lever, and so forth. Accordingly, the dynamic or in-movement simulation was combined with manipulative task so as to permit estimates of the average time-to-response, the positioning precision necessary to provide useful hand function and the myoelectric interference associated with various hand motions.

INSTRUMENTATION

The myoelectric servo boost system, Figure 1, consists of the following components: test stand and couch, arm supporting splint and sleeve, negator springs, electrodes and leads, electromyographic signal conditioning amplifiers and vest, control logic computer, uniplanar power drive, and a power supply.

Test Stand and Couch (Figure 2)

A test stand was fabricated of standard modular storage rack components to house and support a padded couch, power supply, logic circuitry, uniplanar up and down power drive, negator springs, arm support splint, visual feedback directional light display, and manipulative function mounting board. The padded couch configuration was that of the standard Mercury couch as this would allow greater ease of applying test data to a mission oriented myoelectric servo boost system.

Arm Support Splint and Sleeve (Figure 3)

The arm support splint was custom fabricated of chrome plated steel in a configuration most compatible with average arm contours. This ensured the comfort of the test subject and allowed even distribution of arm weight on the support splint. A nylon sleeve encompassed the arm and was laced to secure integration of the test subject's arm with the support splint. The splint was attached to the test stand and allowed four movements of the subject's extended arm at the shoulder joint: extension (down), flexion (up), adduction (in), and abduction (out). As a provision for possible future arm movements, the brace allows flexion and extension of the elbow joint.

Negator Springs (Figures 3 and 4)

To simulate high-G environments, eight constant tension negator springs were mounted on the test rack and the tension members applied to the nylon sleeve in a distribution identical to the average arm weight distribution. With this arrangement, G forces in the range of 1-G to 6-G can be approximated.

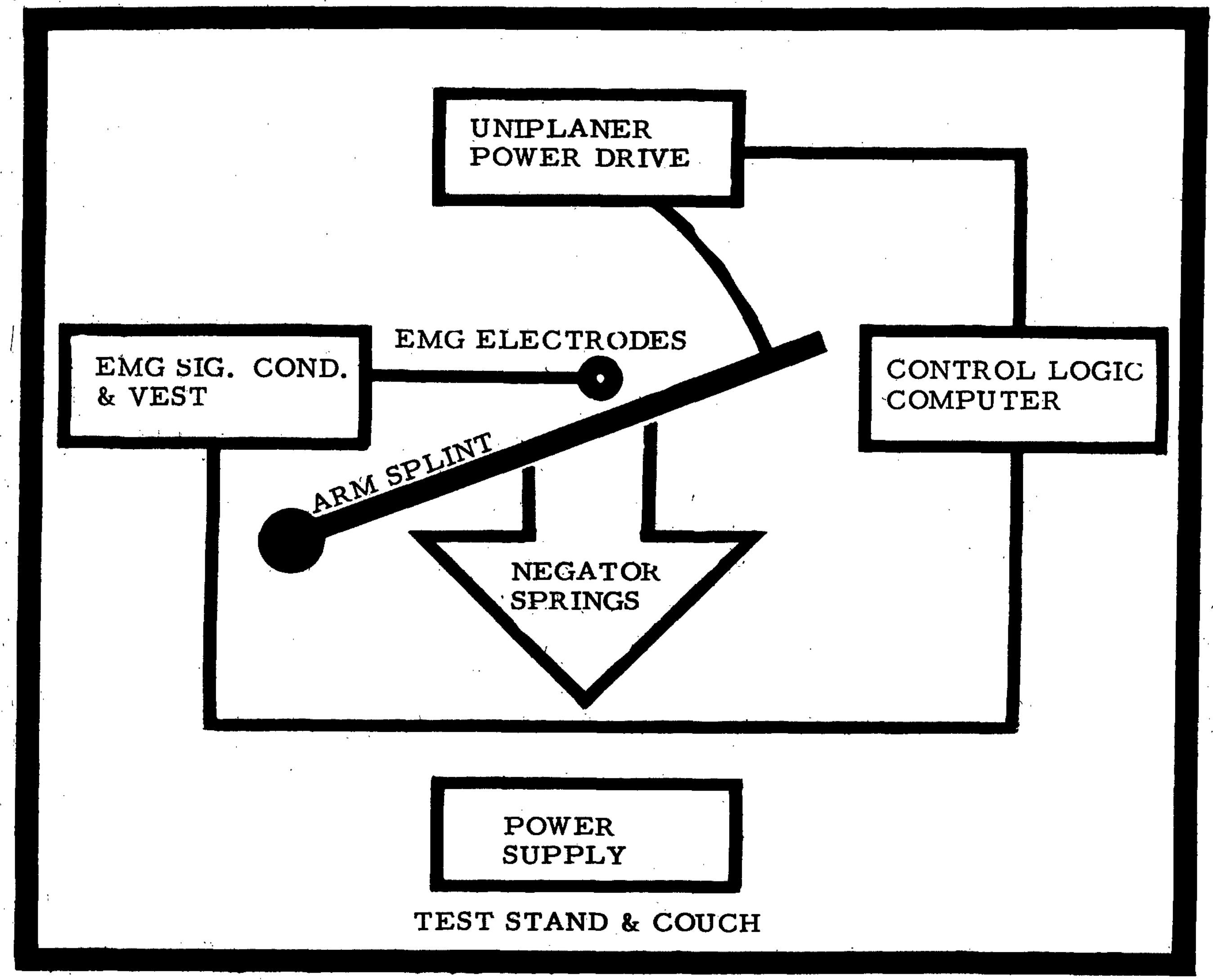


FIGURE 1 MYOELECTRIC SERVO BOOST SYSTEM

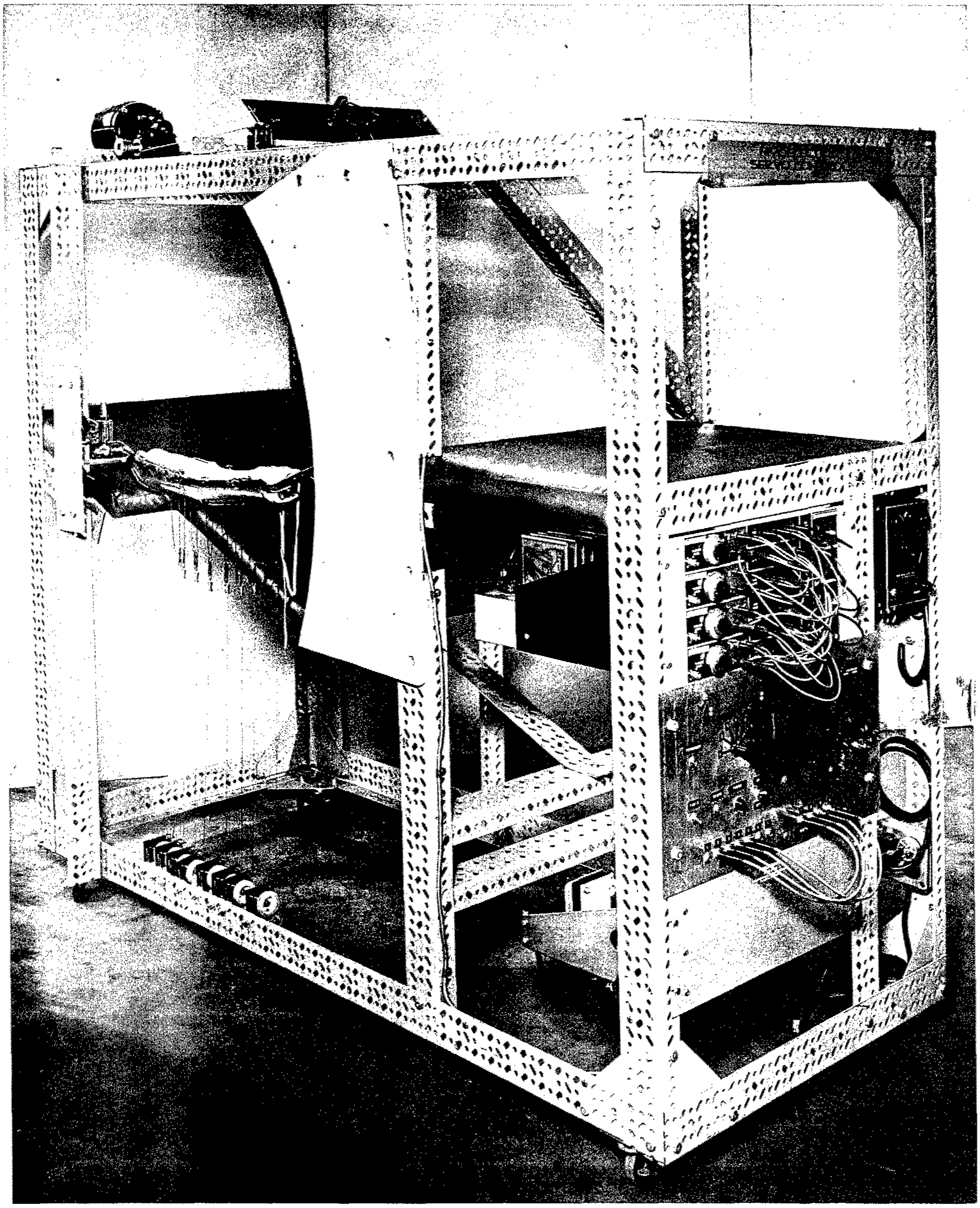


FIGURE 2. TEST STAND AND COUCH

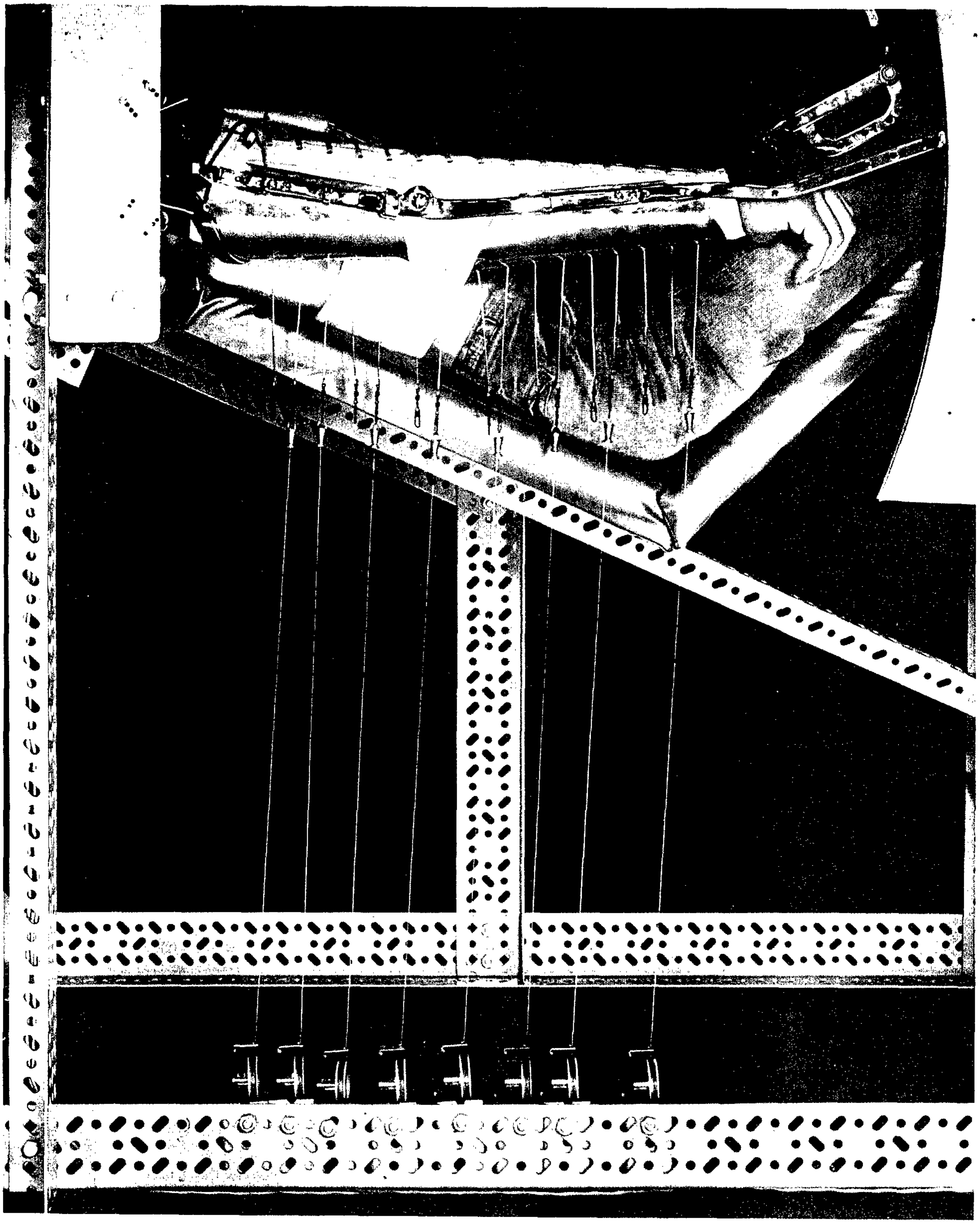


FIGURE 3. ARM SUPPORT SPLINT, SLEEVE AND NEGATOR SPRINGS

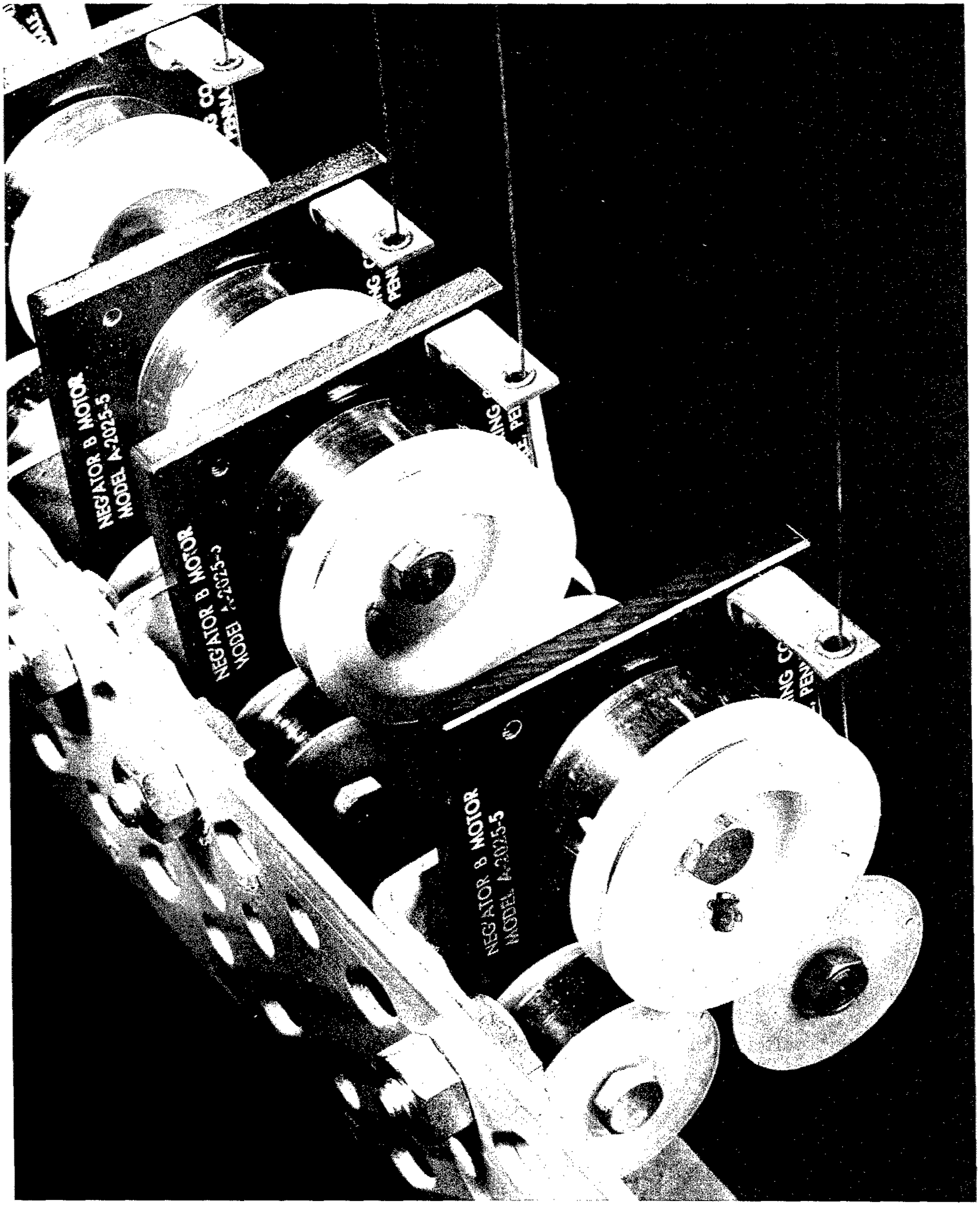


FIGURE 4 NEGATOR SPRINGS

Electrodes and Leads (Figure 5)

Spacelabs-developed low mass silver foil electrodes were selected as giving the "cleanest" EMG signals by minimizing motion artifact. As used, these electrodes were 1.0 to 1.5 cm in diameter and applied to the skin overlying the proper muscle on head or belly. They were affixed with a circumferential rim of Eastman 910 adhesive and a center dab of electrode jelly.

The shielded leads, directly soldered to the electrode foils, were sufficient length to allow full range of motion of the subject's arm.

Electromyographic Signal Conditioning Amplifiers and Vest (Figure 5)

Seven, subminiature, transistorized, high gain, differential, wide band AC amplifiers were fabricated for EMG signal conditioning amplifiers. The frequency bandpass was 0.5 to 5 kc with a gain set at 1000.

A canvas thoracic vest was fabricated to house the EMG amplifiers and was worn by the test subject during the experimental runs. The electrode leads run in channels on the supporting straps. The outputs were terminated at separate jacks to provide flexibility so that any of the seven channels could be plugged into the central logic computer.

Control Logic Computer (Figures 6 and 7)

The central logic computer consisted of four identical logic channels because all the truth tables contained either 3 or 4 muscle combinations. In addition, six "and" gates and two "or" gates were added to the computer in order to supply the required flexibility.

The raw amplified EMG signal from the signal conditioning amplifier was first passed through a high pass filter with a low frequency cutoff of 3 db at 30 cps. The purpose of this filter was to eliminate the large, low frequency baseline shifts which were primarily due to movement artifact. After filtering, the signal passed through a full wave rectifier. To establish a baseline without signal degradation, the output of the filter was connected to an operational amplifier, with feedback time constants that allowed effective peak detecting without the disadvantage of the usually long time constants of a passive detector. The object of the smoothing transformation was to supply a varying dc signal which closely follows the envelope of the EMG signal.

Next, a Schmitt Trigger was used to separate out noise and also standardize all the EMG signals to the same trigger level. As the EMG signal increased in amplitude, it exceeded the preset trigger level and the Schmitt Trigger generated a pulse which existed until the EMG decreased below the trigger level. The raw EMG signal was converted to a square wave pulse that varies from 0 to 10 volts and the width was controlled by the duration of the muscular contraction. Following the Schmitt Trigger was an inverter with an output opposite to the Schmitt Trigger, or a square wave pulse that decreased from 10 volts to 0 volts when the EMG signal exceeded the preset trigger level.

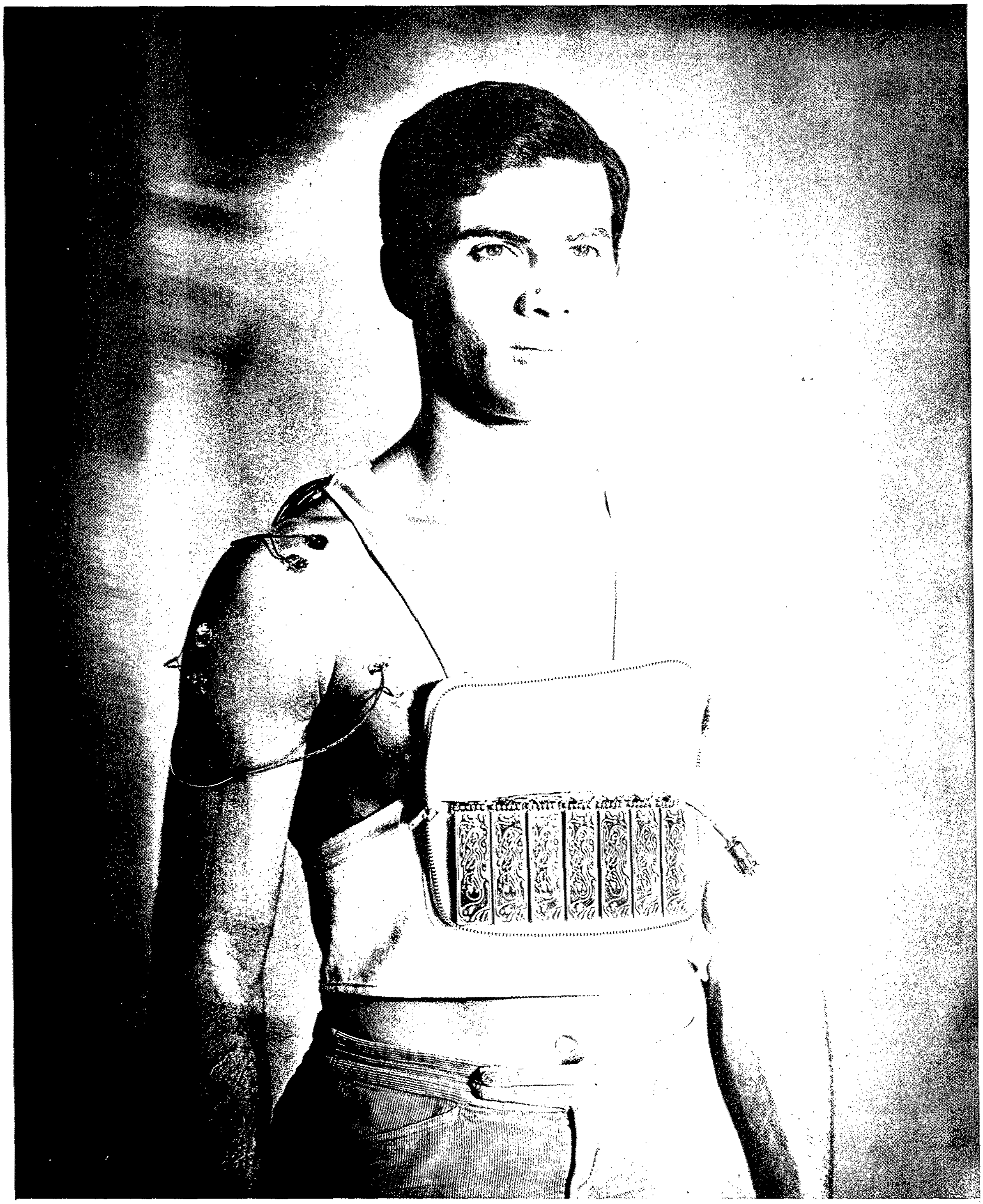


FIGURE 5.

ELECTRODES, LEADS, EMG SIGNAL CONDITIONING AMPLIFIERS AND VEST

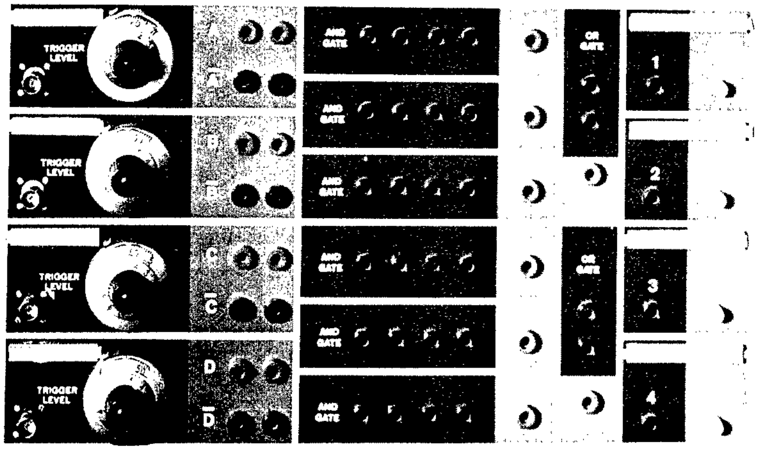


FIGURE 6. CONTROL LOGIC COMPUTER FRONT PANEL

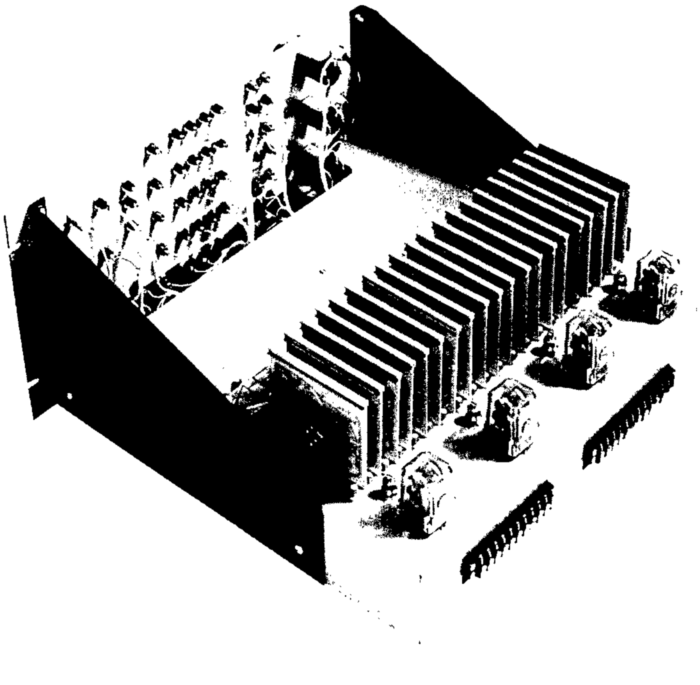


FIGURE 7. CONTROL LOGIC COMPUTER

To complete the logic for the computer, both the Schmitt Trigger and the inverter were necessary. Thus, a single muscle, when contracted, produced both a signal which was 10 volts (Schmitt Trigger) and a signal which was 0 volts (inverter).

The terminology of the truth tables for a relaxed muscle, Anterior Deltoid for example, was represented as follows:

$(AD) = 0$ (Output Schmitt Trigger)

$\overline{(AD)} = 1$ (Output Inverter).

Consequently, when the Anterior Deltoid was contracted the symbologies change state as follows:

$(AD) = 1$ (Output Schmitt Trigger)

$(\overline{AD}) = 0$ (Output Inverter).

The "and" gates of the computer were designed with zero output under normal conditions. However, if all the inputs are in the 1 state, then the output shifts from 0 to 1. Consequently, when a condition is written for a control motion, all of the inputs must be in the 1 state before the "and" gate can pass the command and initiate the function. For example, the equation for up may be written:

$$\text{Up} = (AD)\,(\overline{MD})\,(\overline{PD})\,\overline{(P)}$$

WHERE

Contracted			Not Contracted
(AD)	=	Anterior Deltoid	$(\overline{AD})$
(MD)	=	Medial Deltoid	$(\overline{MD})$
(PD)	=	Posterior Deltoid	$(\overline{PD})$
(P)	=	Pectoralis	$\overline{(P)}$
(B)	=	Biceps	$\overline{(B)}$
(T)	=	Triceps	$\overline{(T)}$

The nomenclature of Boolean algebra interprets $\text{Up} = (AD)\,(\overline{MD})\,(\overline{PD})\,(\overline{P})$ as Anterior Deltoid contracted plus medial deltoid not contracted plus posterior deltoid not contracted plus pectoralis not contracted. Furthermore when a plus (+) appears this is interpreted as or.

In analyzing the above equation for Up it can be seen that 3 of the 4 conditions are already in the 1 state. Consequently, to satisfy the condition, only the anterior deltoid can be contracted. If any other of the above muscles are contracted at this same time, their state will change to 0 and the command will not be initiated.

To handle more complex functions, "or" gates were installed which pass a command if a 1 appears at any of the inputs. Therefore, the "or" gates were programmed from the output of the "and" gates, then either one combination or a second combination of muscles produced the desired output. For example:

$$\text{Down} = (\overline{AD})\,(\overline{PD})\,(T)\,(\overline{B}) \underset{or}{+} (\overline{AD})\,(PD)\,(T)\,(\overline{B})$$

The final section of the computer contained the relay driver which was programmed to operate from the output of either an "and" gate or an "or" gate. Consequently, when the gates switch to a 1 state, the relay contacts closed and performed a control function such as starting and stopping or turning on and off lights.

Training Board and Servodrive Motor (Figure 8)

A training board was fabricated with four lights (up-down, in-out) to display the computer output. The test subject visually determined if the control functions were performed properly. A reversible 115 volt drive motor was also controlled by the above and provided the up and down movement of the arm support splint.

Manipulative Task Board (Figure 9)

A manipulative task board containing a toggle switch and a resistance potentiometer that controlled the brightness of an indicator light was mounted to the test stand at an arm elevation of approximately 60°.

Power Supply

A standard commercially available power supply was obtained and mounted in the test stand. This provided the operating power for the EMG amplifiers, the control logic computer, the training board, and servodrive motor.

DATA ACQUISITION AND ANALYSIS

Phase 1, Derivation of ON-OFF Control Logics

The myoelectric data acquisition system for Phase 1 is schematically diagrammed in Figure 10. The myoelectric signal was obtained through the use of low-mass silver-foil electrode attached to the skin by Eastman 910 adhesive (4). The signal was amplified by a transistorized bioelectric preamplifier.

After preamplification, the myoelectric signal was filtered to eliminate frequencies below 20 cps. Active filters providing an attenuation of at least 18 db per octave were used. The amplified and filtered signals were stored on magnetic tape by a seven-channel FM tape recorder. The DC to 625 cps bandpass of this unit imposed an upper frequency limit on the recorded myoelectric information, but included the frequency band of maximum importance.

The tape recorded signals were subjected to electronic transformation during the subsequent analysis. The equations of the smoothing networks and the analog computer circuits used to synthesize them were described by Weltman and Lyman (5). At the output of the smoothing circuits, the characteristically spiked EMG

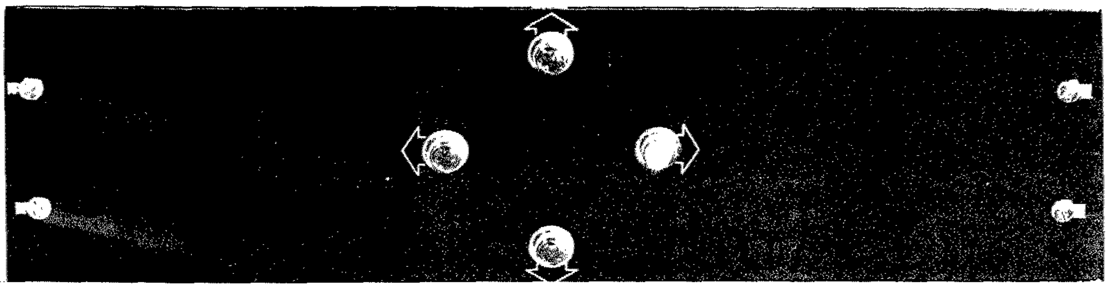
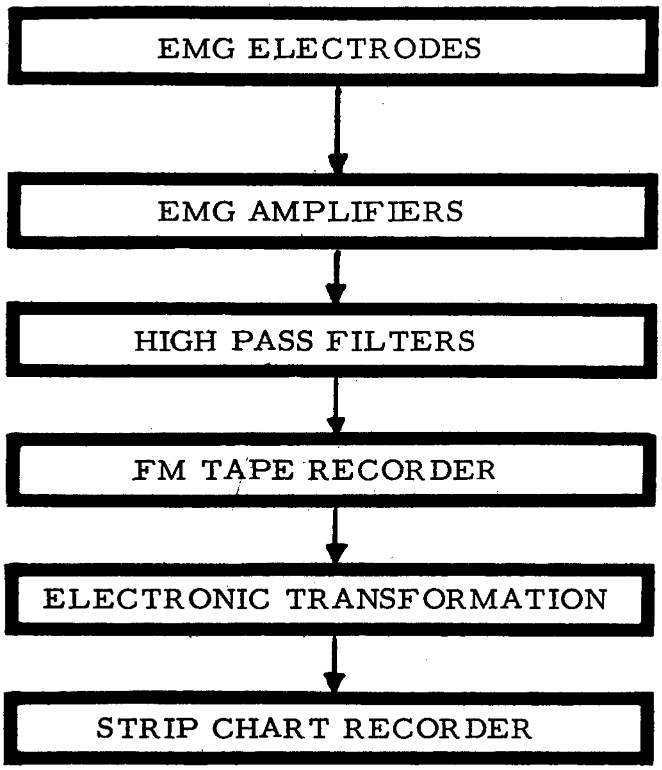


FIGURE 8. TRAINING BOARD

FIGURE 9.

MANIPULATIVE TASK BOARD AND ARM SUPPORT SLING



EMG DATA ACQUISITION & ANALYSIS SYSTEM

FIGURE 10

waveform appeared as a relatively slowly varying voltage whose magnitude was approximately proportional to the mean level of myoelectric activity. These output voltages were recorded on an inkpen recorder and the traces measured by hand to provide the basic myoelectric amplitude data.

Experimental Variables - The experimental variables included: G-loading, the simulated inertial force acting on the arm; arm movement; the linear or rotary maneuver; arm position; the spatial orientation from which movement was initiated; and the anatomical position of the myoelectric sensors.

G-Loading - Three G conditions were simulated: 1-G (or normal gravity), 3-G, and 6-G. The 1-G case was used for comparison purposes. The 3-G case provided a situation where upward movement was possible but difficult, and 6-G loading one in which arm movement was virtually prohibited.

Arm Movement - The six movements examined are diagrammed in Figure 11. The up and rotate movements were opposed by the negator springs, or by gravity in the 1-G case. In, out, and down were opposed by the fixed brace for every G condition. The brace was fixed so as to simulate a push against a finite-lag, servo operated "arm positioner." Because the subject strained against a static support for four of the six movements (up, down, in, out) and moved but slightly for two rotational excursions, the arm movements were considered near-isometric "movement initiations." Some degree of effort and movement-method conformity was imposed by asking the subjects to imagine the movement being completed as they initiated it, to move from the shoulder rather than from the elbow, and to maintain effort at a "comfortable" rather than "extreme" level for the 3-5 sec. recording interval. Complete uniformity, either among subjects or repetitions on a single subject, could not be achieved.

Arm Position - Six arm positions were investigated; they are diagrammed in Figure 12. The discrete positions utilized fell along two planes; the lateral plane (L) at the body's side and the medial plane (M) at body midline. The angles indicated were measured from a 0° reference obtained with the arm held even with the inclined torso. Knee interference prevented the use of medial points lower than M 45°.

Muscle Site - Electrode placement was standardized for the muscle sites indicated in Figure 13. Electrodes were placed over the mass of the biceps, on the lower portion of the triceps and the pectoralis, and on the area of maximum latissimus contraction. When the anterior medial and posterior heads of the deltoid were clearly defined, electrodes were centered on each head.

Control Logic Formulation - Analysis of the recorded myoelectric data was directed primarily toward the derivation of control logics suitable for the composite subject group, at all arm positions and at the higher levels. Thus, while some examination of the effect of the position variable on activity pattern was made, as well as some comparison between the 1-G and other simulated acceleration, these observations were of a subsidiary nature.

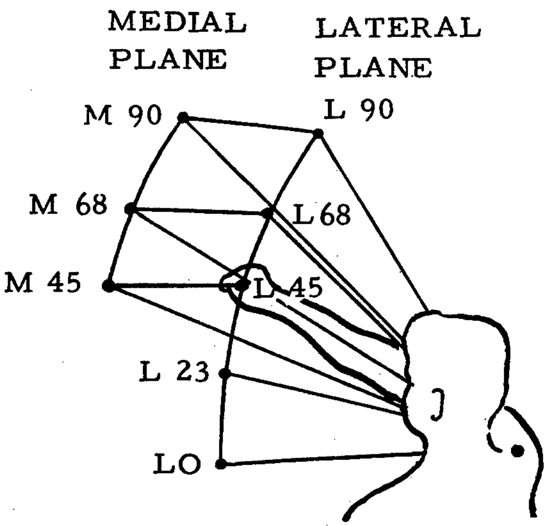


DIAGRAM AND NOMENCLATURE FOR ARM POSITIONS

FIGURE 11

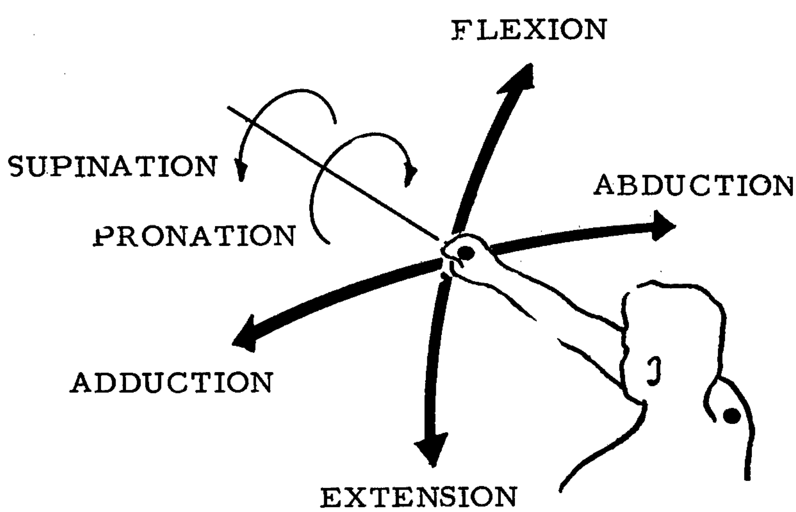
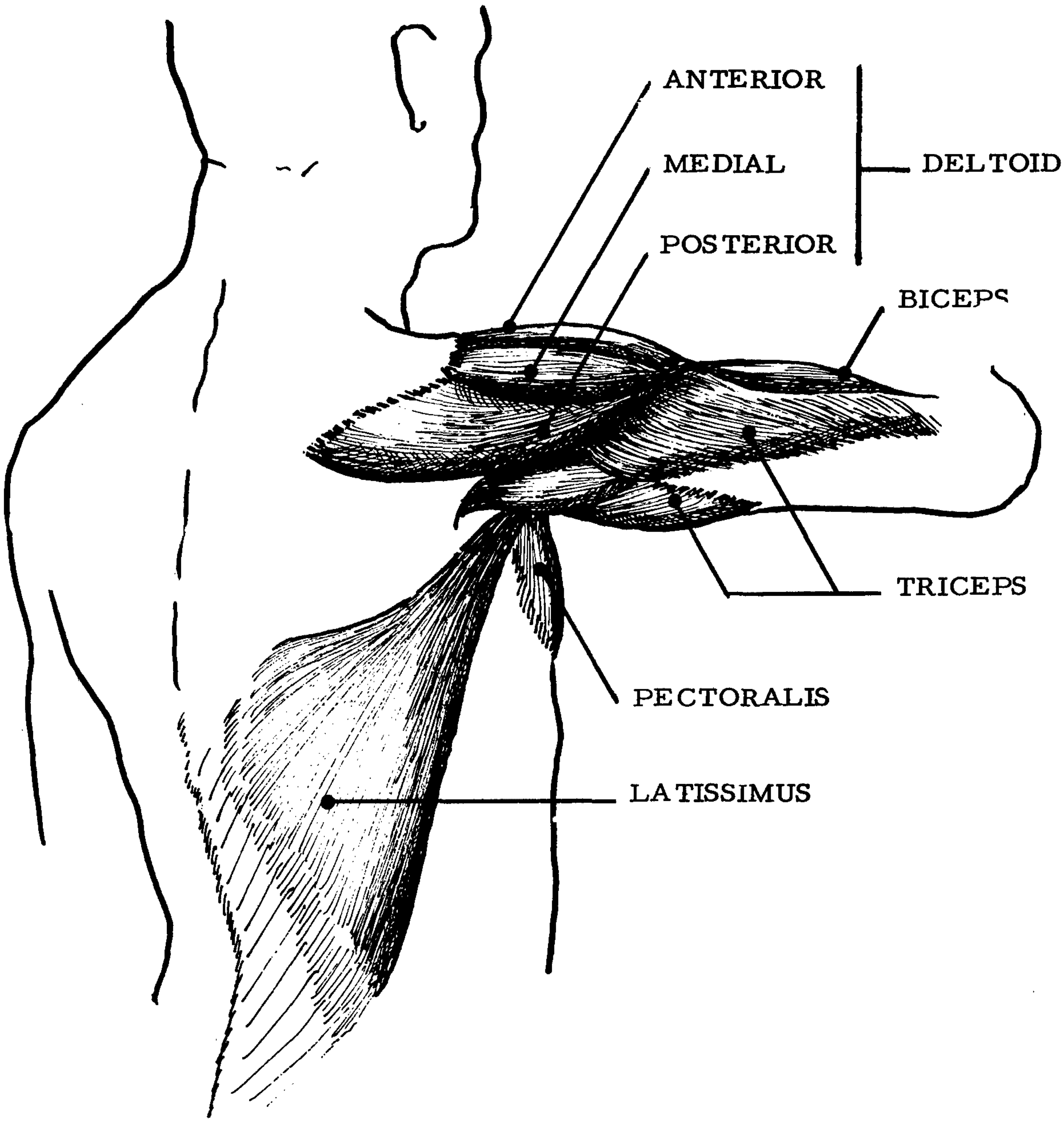


DIAGRAM AND NOMENCLATURE FOR ARM MOVEMENTS

FIGURE 12



LOCATION & NOMENCLATURE FOR MUSCLE SITES

FIGURE 13

The peak myoelectric activity levels measured on the oscillographic records of the smoothed signals were transcribed into detailed tables which specified subject, muscle site, arm position, arm movement, and gravity level. Peak activity level in millimeters was used as an arbitrary measure of myoelectric activity. The three recorded trials were averaged to obtain the transcribed value.

Myoelectric Activity Patterns - Position-free binary activity tables for the individual subjects are presented in Table I (the 1-G case) and Table II (combined 3-G and 6-G cases). Included for each of the G conditions is a composite table containing generalized patterns for the subject group. Patterns for the G-independent movements (in and out) are the same in both tables. No triceps data were obtained for Subject VC.

G-Load Effects - The primary effect of loading on the G-sensitive movements was to amplify signal levels rather than to radically alter activity patterns. As expected, the up movement was especially strongly affected by the simulated increase in effective arm weight. High-amplitude myoelectric signals, in the neighborhood of 2-3 mv peak-to-peak at the skin surface, were elicited from most subjects under the high-G conditions. Although the signal strength characteristic of the high-G runs differed markedly from that observed in the 1-G (or control) condition, little practical difference was seen between the 3-G and 6-G cases for the typical subject. Movement was effectively stopped by the 3-G loading, and since less than maximum strain was requested, the additional restraint imposed by the 6-G situation had a disproportionately small effect on myoelectric activity.

Position Effects - There appeared to be no conclusively generalizable effect of arm position on either the myoelectric signal magnitudes or the activity patterns associated with the arm movements studied. There was some indication, however, that the patterns were less ambiguously defined at the central positions than at the L 0°, L 68°, and M 68° points. The lack of strong effects was interpreted as favorable to subsequent myoelectric control, since by implication a selected logic would be effective over the entire volume swept out by a servoed arm splint. It is important to remember that the effects considered here were of an extremely gross nature; that is, affecting the binary ON-OFF control tables exclusively. It is almost certain that because of the variations in pre-contractile muscle length imposed by the arm positions assumed, some differences existed in myoelectric signal magnitudes.

Individual Differences - As in the examination of G-load effects, observed differences among subject were associated more with the overall myoelectric activity level than with the activity patterns elicited by arm movement. General similarity of activity pattern is seen in Table II, but it is also obvious that individual differences did exist. To some extent, these differences in binary pattern reflect the impossibility of rigorously standardizing movement execution in an open-loop situation. The lack of extremely divergent responses indicates that training subjects to elicit predetermined "most common" patterns by means of visual feed-back and immediate knowledge of results is a feasible approach (3).

TABLE I

MYOELECTRIC ACTIVITY PATTERNS IN THE 1-G CONDITION

		ARM MOVEMENT					
	MUSCLE	Up	R-In	R-Out	Down	In	Out
Subject JB	Latissimus	1	1	0	1	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	0	0	1
	Biceps	1	0	1	0	1	0
	Triceps	0	1	1	0	0	1
	Pectoralis	0	0	0	0	1	0
Subject JA	Latissimus	0	0	0	0	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	0	0	0
	Biceps	1	0	1	0	1	0
	Triceps	0	1	1	1	0	1
	Pectoralis	0	1	0	0	1	0
Subject VC	Latissimus	1	1	1	0	0	0
	Ant. Deltoid	0	0	0	0	0	0
	Pos. Deltoid	1	0	0	1	0	1
	Biceps	0	0	0	0	1	0
	Triceps	-	-	-	-	-	-
	Pectoralis	0	0	0	0	1	0
Subject GW	Latissimus	0	0	0	0	0	0
	Ant. Deltoid	1	0	0	0	0	0
	Pos. Deltoid	0	0	0	0	0	1
	Biceps	0	0	1	0	1	0
	Triceps	0	1	0	0	0	0
	Pectoralis	0	0	0	0	1	0
Subject DP	Latissimus	0	0	0	0	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	0	0	1
	Biceps	1	0	0	0	1	0
	Triceps	0	1	1	0	0	1
	Pectoralis	0	0	0	0	1	0
Generalized Subject Trend	Latissimus	0	0	0	1'	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	1'	0	1
	Biceps	1	0	1	0	1	0
	Triceps	0	1	1	1'	0	1
	Pectoralis	0	0	0	0	1	0

One Observation Only

TABLE II

MYOELECTRIC ACTIVITY PATTERNS IN THE HIGH-G CONDITIONS

		ARM MOVEMENT					
	MUSCLE	Up	R-In	R-Out	Down	In	Out
Subject JB	Latissimus	1	0	0	1	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	0	0	1
	Biceps	1	0	1	0	1	0
	Triceps	0	1	0	0	0	1
	Pectoralis	0	0	0	0	1	0
Subject JA	Latissimus	1	0	0	0	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	0	0	0
	Biceps	1	0	1	0	1	0
	Triceps	0	1	0	1	0	1
	Pectoralis	1	1	0	0	1	0
Subject VC	Latissimus	0	0	0	0	0	0
	Ant. Deltoid	1	1	0	0	0	0
	Pos. Deltoid	1	0	0	1	0	1
	Biceps	1	0	1	0	1	0
	Triceps	-	-	-	-	-	-
	Pectoralis	0	0	0	0	1	0
Subject GW	Latissimus	0	0	0	0	0	0
	Ant. Deltoid	1	0	0	0	0	0
	Pos. Deltoid	0	0	0	0	0	1
	Biceps	1	0	1	0	1	0
	Triceps	0	0	0	0	0	0
	Pectoralis	0	0	0	0	0	0
Subject DP	Latissimus	0	0	0	0	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	0	0	1
	Biceps	1	0	1	0	1	0
	Triceps	0	1	1	0	0	1
	Pectoralis	0	0	0	0	1	0
Generalized Subject Trend	Latissimus	0	0	0	1'	0	0
	Ant. Deltoid	1	0	0	0	0	1
	Pos. Deltoid	0	0	0	1'	0	1
	Biceps	1	0	1	0	1	0
	Triceps	0	1	0	1'	0	1
	Pectoralis	0	0	0	0	1	0

'One Observation Only

A second major cause of pattern differences was the variability of myoelectrical activity in the latissimus and arm muscles. The latissimus site was the most difficult to instrument reliably and rarely produced a significant signal. Use of the biceps and triceps varied widely in the subject group. Apparently, it was quite difficult to separate elbow flexion and extension from pure shoulder movement without supplementary feedback. The deltoid, in particular the anterior deltoid, was the most active muscle for all five subjects. Pre-eminance of this muscle in arm maneuvers has been noted in previous work (5). An idea of inter-subject and inter-muscle differences in signal strength can be obtained from the data of Table III which presents the recorded signal levels at the biceps and deltoid muscles during the up movement under simulated 6-G conditions in the central range of the transverse position plane.

Difficulties were anticipated in the interpretation of the pectoralis signals because of the frequent presence of cardioelectric activity at that site. Interestingly, these difficulties never materialized. Electrode placement on the muscle's underside eliminated some of the interference at the source, and the combination of highpass filtering and smoothing apparently minimized the effects of the remainder.

Control Logic Tables - If it is assumed that only the high-G conditions are of importance for control applications, it is possible to utilize the data of Table II to formulate binary logics for the four movements of greatest interest (i.e., up, down, in, and out) using sets of three or four muscle sites. Tables IV and V represent the two best three-muscle logics. It is seen from the accompanying Boolean expressions that observation of the anterior and posterior deltoid sites suffices to discriminate three motions (up, down, out), and that the pectoralis, medial deltoid, or biceps is needed to identify the fourth (in) movement.

It is possible to introduce a slightly greater degree of control redundancy, and accordingly a potential increase in reliability, by utilizing four rather than three muscles in the control set. Three logics of this type are seen in Tables VI, VII, VIII, and IX. In this case an a priori choice as to relative superiority is more difficult to make.

In addition to the logic tables formulated at the Biotechnology Laboratory, another logic matrix was derived by the principal investigators which enabled the subject to perform readily the four movements of the arm. This logic utilized the three heads of the deltoid muscle (anterior, medial and posterior) along with the pectoralis muscle.

Phase II, Task Simulation

Static Task Simulation - Four experimental subjects, all engineering students at a nearby college, were instrumented with the low mass electrode over the proper muscle site. The myoelectric signal was processed through the signal conditioner amplifier and control logic computer as described in the instrumentation section of this report

TABLE III

A COMPARISON OF RECORDED MYOELECTRIC SIGNAL STRENGTH

SUBJECT	MUSCLE SITE	
	Biceps	Ant. Deltoid
JB	25	60
JA	40	70
VC	20	52
GW	3	10
DP	12	31

TABLE IV

A THREE-MUSCLE CONTROL LOGIC

MUSCLE SITE			MOVEMENT LOGIC
Anterior Deltoid	Posterior Deltoid	Pectoralis	
1	0	0	Up = $(AD)(\overline{PD})$
1	0	1	
0	1	0	Down = $(\overline{AD})(PD)$
0	0	1	In = $(\overline{AD})(\overline{PD})(P)$
1	1	0	Out = $(AD)(PD)$

TABLE V

A THREE-MUSCLE CONTROL LOGIC

MUSCLE SITE			MOVEMENT LOGIC
Anterior Deltoid	Posterior Deltoid	Biceps	
1	0	0	
1	0	1	Up = $(AD)(\overline{PD}) + (AD)(B)$
1	1	1	
0	1	0	Down = $(\overline{AD})(PD)(\overline{B})$
0	0	1	In = $(\overline{AD})(\overline{PD})(B)$
1	1	0	Out = $(AD)(PD)(\overline{B})$

TABLE VI

A FOUR-MUSCLE CONTROL LOGIC

MUSCLE SITE				MOVEMENT LOGIC
Anterior Deltoid	Posterior Deltoid	Triceps	Pectoralis	
1	0	0	0	Up = $(AD)(\overline{PD})$
0	0	1	0	
0	1	0	0	Down[1] = $(\overline{AD})(PD) + (T)$
0	1	1	0	
0	0	0	1	In = (P)
1	1	0	0	Out = $(AD)(PD)$
1	1	1	0	

Notes:

[1] Rotate-in can be used to augment.

TABLE VII

A FOUR-MUSCLE CONTROL LOGIC

MUSCLE SITE				MOVEMENT LOGIC
Anterior Deltoid	Posterior Deltoid	Biceps	Pectoralis	
1	0	0	0	Up = (AD) ($\overline{PD}$)
1	0	1	0	
0	1	0	0	Down = ($\overline{AD}$) (PD)
0	0	0	1	In[1] = ($\overline{AD}$) (B) + (P)
0	0	1	0	
0	0	1	1	
1	1	0	0	Out = (AD) (PD)

TABLE VIII

A FOUR-MUSCLE CONTROL LOGIC

MUSCLE SITE				MOVEMENT LOGIC
Anterior Deltoid	Posterior Deltoid	Biceps	Triceps	
1	0	0	0	Up = (AD) ($\overline{PD}$)
1	0	1	0	
1	1	1	0	
0	1	0	1	Down[1] = ($\overline{PD}$) (T) + ($\overline{AD}$) (PU) (T)
0	0	0	1	
0	1	0	1	
0	0	1	0	In[2] = ($\overline{AD}$) (B)
1	1	0	0	Out = (AD) (PD)
1	1	0	1	

Notes:

[1] Rotate-in can be used to augment.

[2] Rotate-out can be used to augment.

TABLE IX

A FOUR-MUSCLE CONTROL LOGIC

MUSCLE SITE				MOVEMENT LOGIC
Anterior Deltoid	Medial Deltoid	Posterior Deltoid	Pectoralis	
1	0	0	0	Up = $(AD)(\overline{MD})(\overline{PD})(\overline{P})$
0	0	1	0	Down = $(\overline{AD})(\overline{MD})(PD)(\overline{P})$
0 1	0 0	0 0	1 1	In = $(\overline{AD})(\overline{MD})(\overline{PD})(P)$ or $(AD)(\overline{MD})(\overline{PD})(P)$
0	1	0	1	Out = $(\overline{AD})(MD)(\overline{PD})(\overline{P})$

Six logic matrices were evaluated and Tables X to XV list the results in the format of successful movements to trial movements. In addition, trigger voltage settings are tabulated.

The difficulty experienced by the subjects in obtaining out and in movements utilizing the control logic formulations led to the development of logic Table IX. With this logic programmed in and the anterior, medial and posterior heads of the deltoid muscle along with the pectoralis muscle being instrumented, the subjects were able to achieve the four movements; up, down, in, and out, without difficulty.

The medial head of the deltoid was programmed to provide the necessary resolution of out movements. The pectoralis muscle in all cases was found to be imbued with in movements of the extended arm. The data show that the subjects were almost completely successful in exercising the four movements tested at both the 0° position and the lateral 60° position. A third position, 60° medial was chosen so that these three positions would define a plane in which the subject could perform manipulative functions. Only two of the four subjects were evaluated at the 60° medial position. One was able to perform all four movements without error, whereas the other was unable to obtain in and out. It is believed that with a longer training period he too could have been able to perform the in and out movements.

It will be noted that none of the subjects experienced any difficulty with up and down on the six logic tables tested. This was due to the degree of resolution obtained in contraction of the anterior deltoid and posterior deltoid muscles involved in up and down movements. However, no amount of training enabled the subjects to contract and relax selectively those muscles programmed for out movements utilizing the first five logic tables.

A training curve was evident in that the percentage of successful movements increased with the number of trials to reach a plateau level. This success to trial figure was taken to represent the optimum achievable for the particular logic table being tested. Towards the end of the individual experiments, which generally ran three to four hours, a definite fatigue effect was observed. The success to trial ratio decreased as the subject became fatigued and was unable to contract selectively the proper muscles.

The trigger settings were generally about 540 divisions which corresponded to approximately two volts (see Figure 14.) At this level, the signal to noise ratio was four to one. There was a definite individual variation in the trigger settings that was necessitated by the difference in muscle mass distribution on the four subjects.

On the basis of the results of the static simulation runs, logic Table IX was chosen as the most reliable and was utilized for the other two tasks of the experimentation.

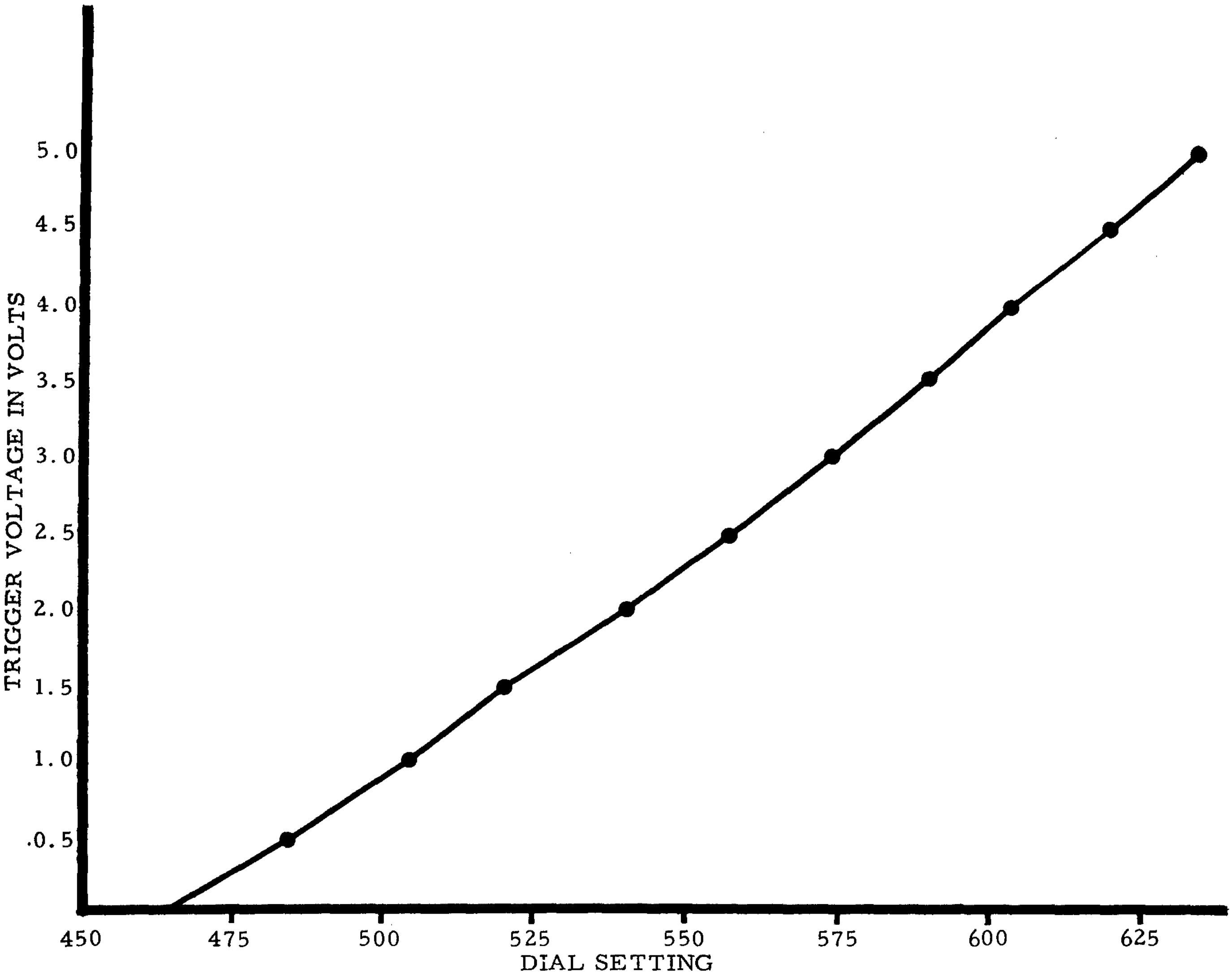


FIGURE 14 CONTROL LOGIC COMPUTER — TRIGGER LEVELS

TABLE X

A THREE MUSCLE CONTROL LOGIC
STATIC TASK SIMULATION

POSITION	MOVEMENT	SUBJECT				COMPOSITE
		A	B	C	D	
0°	Up	5/5	5/5	5/5	5/5	20/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	4/5	0/5	5/5	5/5	14/20
	Out	3/5	0/5	0/5	0/5	3/20
60°L	Up	5/5	5/5	5/5	5/5	20/20
	Down	4/5	5/5	5/5	4/5	18/20
	In	5/5	0/5	4/5	5/5	14/20
	Out	0/5	0/5	0/5	0/5	0/20
60°M	Up	5/5			5/5	10/10
	Down	2/5			4/5	6/10
	In	2/5			5/5	7/10
	Out	0/5			0/5	0/10
Trigger Settings	AD	650	540	530	525	
	PD	540	540	520	580	
	P	530	540	503	560	

TABLE XI

A THREE MUSCLE CONTROL LOGIC
STATIC TASK SIMULATION

POSITION	MOVEMENT	SUBJECT				COMPOSITE
		A	B	C	D	
0°	Up	5/5	3/5	5/5	5/5	18/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	4/5	5/5	0/5	5/5	14/20
	Out	0/5	0/5	0/5	0/5	0/20
60°L	Up	5/5	5/5	5/5	5/5	20/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	4/5	5/5	0/5	5/5	14/20
	Out	0/5	0/5	0/5	0/5	0/20
60°M	Up	5/5	5/5	5/5	5/5	20/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	0/5	2/5	0/5	0/5	2/20
	Out	0/5	0/5	0/5	0/5	0/20
Trigger Settings	AD		540	540	530	
	PD		540	540	560	
	B		540	540	525	

TABLE XII

A FOUR MUSCLE CONTROL LOGIC
STATIC TASK SIMULATION

POSITION	MOVEMENT	SUBJECT				COMPOSITE
		A	B	C	D	
0°	Up			5/5	5/5	10/10
	Down			5/5	5/5	10/10
	In			5/5	5/5	10/10
	Out			2/5	0/5	2/10
60°L	Up			5/5	5/5	10/10
	Down			5/5	5/5	10/10
	In			5/5	5/5	10/10
	Out			1/5	0/5	1/10
60°M	Up			5/5		5/5
	Down			5/5		5/5
	In			0/5		0/5
	Out			1/5		1/5
Trigger Settings	AD			540	570	
	PD			540	525	
	T			540	570	
	P			540	540	

TABLE XIII

A FOUR MUSCLE CONTROL LOGIC
STATIC TASK SIMULATION

POSITION	MOVEMENT	SUBJECT				COMPOSITE
		A	B	C	D	
0°	Up	5/5	5/5	5/5	5/5	20/20
	Down	5/5	4/5	5/5	5/5	19/20
	In	5/5	5/5	5/5	5/5	20/20
	Out	0/5	0/5	0/5	0/5	0/20
60°L	Up	5/5	5/5	5/5	5/5	20/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	5/5	4/5	1/5	5/5	15/20
	Out	0/5	0/5	1/5	0/5	1/20
60°M	Up			5/5	5/5	10/10
	Down			5/5	5/5	10/10
	In			0/5	5/5	5/10
	Out			1/5	0/5	1/10
Trigger Settings	AD			540	525	
	PD			540	535	
	B			540	525	
	P			540	550	

TABLE XIV

A FOUR MUSCLE CONTROL LOGIC
STATIC TASK SIMULATION

POSITION	MOVEMENT	SUBJECT				COMPOSITE
		A	B	C	D	
0°	Up	0/5	5/5	5/5	5/5	15/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	0/5	5/5	0/5	5/5	10/20
	Out	5/5	5/5	0/5	0/5	10/20
60°L	Up	5/5	5/5	5/5	5/5	20/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	0/5	3/5	0/5	0/5	3/20
	Out	5/5	0/5	1/5	0/5	6/20
60°M	Up		4/5	5/5	5/5	14/15
	Down		4/5	5/5	5/5	14/15
	In		2/5	0/5	0/5	2/15
	Out		0/5	0/5	0/5	0/15
Trigger Settings	AD	492	528	540	525	
	PD	460	532	540	535	
	B	428	538	540	525	
	T	460	540	540	550	

TABLE XV

A FOUR MUSCLE CONTROL LOGIC
STATIC TASK SIMULATION

POSITION	MOVEMENT	SUBJECT				COMPOSITE
		A	B	C	D	
0°	Up	5/5	4/5	5/5	5/5	19/20
	Down	5/5	5/5	5/5	5/5	20/20
	In	5/5	4/5	4/5	5/5	18/20
	Out	5/5	5/5	5/5	5/5	20/20
60°L	Up	5/5	5/5		5/5	15/1[illegible]
	Down	5/5	4/5		5/5	14/15
	In	5/5	5/5		5/5	15/15
	Out	5/5	4/5		5/5	14/15
60°M	Up	5/5		5/5		10/10
	Down	5/5		5/5		10/10
	In	5/5		0/5		5/10
	Out	5/5		0/5		5/10
Trigger Settings	AD	650	540	541	570	
	MD	765	540	532	570	
	PD	540	540	540	525	
	P	530	540	542	540	

Dynamic Task Simulation - The same four subjects were used in the dynamic task simulations. The arm support splint moved in a track that allowed only up and down motions. The speed of movement was controlled manually by the experimenter. All four subjects were able to control up and down motion of the arm splint after a learning period of less than one or two minutes. Relaxation was important in cutting down the learning period as there was a strong tendency to tense all of the shoulder girdle muscles. Instruction as to what muscles were involved in the selected movements and their anatomical location was invaluable in enabling the subjects to exercise complete control over up and down motion. Both auditory and visual commands as to the limit of excursion of the splint were fulfilled with up to 90 percent success up to an arm support splint speed of 13.5 degrees per second. At speeds greater than this, there was much oscillatory hunting about the termination point, especially in short tracking maneuvers. Of great significance was the ability of the subjects to initiate and sustain either an up or down movement and then to either correctly register in or out while the brace was moving. The subjects were able to follow visual and auditory cues in performing tracking movement with a high percentage of success.

Manipulative Task Simulation - A simple manipulative task board consisting of a toggle switch that turned On and OFF a light and a resistance potentiometer that controlled the brightness of the indicator light was used to ascertain the effect of motor speed on simple manipulative functions. The task was to initiate up movement, sustain it to approximately 60° inclination and turn the light off. At arm support splint speeds up to 6.8 degrees per second, no difficulty was encountered in the following phases of the task: initiate, sustain, stop, perform manipulative task.

Performance of the manipulative task did not trigger up, down, in or out indicating the muscles instrumented were not involved in the five tasks. At splint speeds greater than 6.8 degrees per second, a degradation in fine positioning ensued that was progressive with increasing splint speed.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The results obtained from this investigative program proved to be a significant advance in the successful utilization of the myoelectric potentials through a pre-programmed computer to control a servo boost system. The myoelectric control system functioned accurately for 90% of the selected test program including tests conducted with simulated increased accelerative forces.

The evolved logic table utilizing the three heads of the deltoid muscle and pectoralis muscle proved to be extremely successful for the control of up, down, in, and out movements of the extended arm. The subject utilizing the logic Table IX was able to control in and out motions while the arm was moving up or down.

For the ON-OFF type of servo system used in this study, a splint speed of 13.5 degrees per second appears to be the optimum for gross movements and 6.8 degrees per second optimum for fine manupulative movement.

The subject was able to control the arm in tracking maneuvers utilizing both visual and auditory cues.

The subject utilizing the present myoelectric servo boost system was able to perform manipulative functions successfully.

RECOMMENDATIONS

The following recommendations are made to suggest the direction of further effort in future programs.

1. Proportional control of the speed of arm movement by relating contractive effort to speed of movement should be incorporated into future systems.

2. The degrees of freedom or range of motion of the joints should be expanded to include the elbow, wrist, and digits.

3. The arm support splint should be made in a manner compatible for incorporation of self contained actuators of motion.

4. The logics, techniques, and instruments developed from this program should be applied to prosthetic devices.

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